TECHNICAL SESSION PREPRINTS of the AMERICAN ASTRONAUTICAL SOCIETY

516 Fifth Avenue, New York 36, New York

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AN EARTH-ORIENTED COMMUNICATION SATELLITE OF THE PASSIVE TYPE

by

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6th National Annual Meeting
18-21 January 1960
New York City, New York

Preprint No. 60-4

TMX-56598

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ABSTRACT

A passive communication satellite for global communication is described in which the reflecting surface is an erectable spherical segment of a very large sphere (which as a complete sphere would be impractical to build) and the segment is oriented continuously toward the center of the earth. Use of the spherical segment is proposed as a compromise between the low reflecting efficiency of a smaller complete sphere and the high pointing accuracy required for a plane reflecting surface.

The satellite after injection into orbit is oriented toward the earth's center by an horizon-scan stabilization system. The orbit is modified, if necessary, to achieve a circular orbit. The reflecting surface is subsequently erected. To achieve a long lifetime of the attitude control system a secondary erectable structure is employed that separates the payload and the last-stage rocket booster into two masses, forming a dumbbell configuration. This final configuration is then passively stabilized by the method of gravitational-centrifugal force gradient. At altitudes higher than 3,000 miles the long-term control system would employ inertial-reaction controls or utilize the solar light pressure which is also a major perturbation. The size and weight of the satellite can be appreciably reduced by orienting the axis of the segment reflector to bisect the angle between the satellite and two ground stations in lieu of orientation toward the earth's center.

Factors affecting optimization of the satellite with respect to reduction of transmitter power and size of antennas for the ground stations and satellite weight are considered. The stabilization and erection systems are discussed. Some comparisons are made with respect to the experimental 100-foot-diameter spherical relay satellite under development by the NASA.

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INTRODUCTION

At the Langley Research Center of the NASA we are studying some novel lightweight erectable structures for use in the space environment and for several kinds of space missions. Our research objectives in the communication application are twofold. They are (1) to investigate use of such structures in configurations of high-gain directive antennas for satellite and deep space communication and (2) to extend earth communication links using relay satellites. This paper is concerned with the second objective and in particular with desirable configurations of the passive or forward-scattering type of relay satellite that may be feasible to construct and to deploy in orbit. Figure 1 illustrates the problem and serves to bring out several of the factors that can influence the design of the satellite.

At this ground point we assume that there is a station A that is transmitting a narrow beam of electromagnetic radiation in S- or X-band to the satellite when it is mutually visible to both station A and to a distant receiving station B located perhaps on another continent. The function of the passive relay satellite is to intercept a maximum amount of the beam from A and to reflect a maximum amount of the intercepted beam to the receiving station B, with a minimum of signal distortion and fading attributable to the satellite itself. Obviously in this situation the distance between ground stations, the number of stations, and their relative geographical location are very important considerations. Of not lesser importance are the size and efficiency of the ground antennas, the transmission frequency, bandwidth and modulation, the transmitter power, and the receiver sensitivity. For the satellite factors, there are the weight and complexity of the payload, the reflector configuration, size and orientation requirements, the number of relays needed to maintain a certain probability of continuous communication and the orbit altitude and inclination to the equator. Several of these factors are explicitly related in the expression that can be derived for the power lost in transmitting from A to B via the satellite. The number of satellites required is difficult to assess except for special cases. While many of these factors have been considered in the current literature (refs. 1, 2, 3, and 4, for example) let us look briefly at two of them.

In table I are listed some principal cities of distant countries and of the two new states, Alaska and Hawaii. These cities might profitably be linked through New York, Los Angeles, and Honolulu by a satellite relay system. Obviously in some cases there are language barriers

in addition to ocean barriers. This factor increases the need for a broadband television capability as an aid in communication. As Pierce has pointed out (in ref. 1) the 3,500 miles between New York and London can be reduced by overland microwave links, leaving about 2,060 miles for a satellite link. However, for many of the cases shown here, distances of the order of 2,600 and 5,000 miles are unavoidable.

Let us look also at the availability of large ground-based parabolic antennas as indicated by table II. We see that extremely large dishes can be available that would greatly reduce the size of passive reflector required in orbit. A trade-off in this direction appears necessary at this stage of the space vehicle art.

NASA PROJECT ECHO

The first satellite communication experiment being undertaken by the NASA is Project Echo. This project has been described in the December 14 issue of Aviation Week magazine (ref. 5) so I assume most of you are familiar with the project. Let me add just a few comments at this point. The work on the satellite payload is in process at the Langley Research Center. As you may recall, the satellite relay is of the passive type, a 100-foot-diameter Mylar plastic sphere coated with 4 pounds of aluminum. In figure 2 it is shown in the inflated condition. It is inside a Naval hangar at Weeksville, North Carolina.

The payload is being tested in several ways prior to the first orbiting flight. Ground tests of 30-inch, 12- and 24-foot models have been made in vacuum chambers of up to 41-foot diameter. The initial opening and partial inflation of the full-scale payload has likewise been tested in a 41-foot chamber. The inflation of the 100-foot sphere in the Naval hangar permitted a check on the strength of the sphere, particularly the seams. Vibration and dynamic load tests of the payload have also been conducted. The first flight test of the payload, including the last stage for the orbiting vehicle was conducted on the evening of October 28, 1959. This was a two-stage ballistic probe. One result of this test was that the initial inflation with the residual air and the water vapor system was too rapid. The sphere may have been partially damaged although it was strongly visible for 13 minutes. Substitution of a slower-acting benzoic acid system for the water system is being considered. This would also avoid the concentrated mass of the water system. Two more suborbital flight tests are in process.

The duration that inflation pressure can be maintained by both the initial and secondary inflation systems is estimated to be of the order of 20 days. This is long enough to determine the reflecting efficiency of the sphere in orbit. After the inflation pressure is lost, surface

irregularities may develop and reduce the efficiency of reflection. The sphere may collapse under the combined effects of residual angular velocity and dynamic unbalance due to variations in the thickness of the material and two small beacons that may be attached. There are also thermal gradients that may initiate collapse. It would be a pleasant surprise if the sphere retains its effectiveness for many months.

The payload weight is summarized in table III. The weight of the Project Echo sphere is 136 pounds and the total payload weight is 187 pounds. An estimate for a rigidized version is given on the right. In this case the 100-foot sphere is assumed to be constructed of inflatable honeycomb. This method of fabrication would approximately triple the weight but greatly increase the probability of retaining the spherical shape after loss of the inflation pressure.

In addition to the NASA test path between Goldstone, California, and Holmdel, New Jersey, a distance of 2,300 miles, the Air Force is establishing a second test path. This is between Rome, New York, and Trinidad with transmission from Trinidad at about 2,270 Mcs, using an 84-foot dish, and reception at Rome, using a 34-foot dish.

EARTH-ORIENTED, PASSIVE RELAY

A presumed advantage in employing a large sphere as a passive relay is the fact that the sphere does not require orientation toward the earth (ref. 2). Hence a sphere is simpler and should be more reliable. However, offsetting this is the large size of sphere that is required and the resulting limitations on full-scale ground testing. This places the major burden on relatively few flight tests conducted under difficult conditions of observation. The requirement for a large sphere arises from the fact that the reflection from the sphere is almost uniformly isotropic (as noted by refs. 2, 6, 7, and 8). Handelsman (ref. 2) has considered the use of flat directive reflectors in a "stationary" 24-hour equatorial orbit. He estimates that for 1,000 Mcs transmission a reflector 23 feet across should give 1,000-mile-diameter spot coverage and require a pointing accuracy of better than 1°. However, to maintain this 1,000-mile-diameter coverage and the pointing accuracy requirement (which is a reasonable requirement) at frequencies above 1,000 Mcs, the diameter of the reflector must be made smaller. Hence simultaneous transmission at different frequencies in S- or X-band within the tolerances noted is not possible, since at the higher frequencies the "spot" becomes smaller and the pointing accuracy very great.

A compromise solution to the problem of the reflector configuration is suggested in figure 3. A segment of a sphere would be employed. The

segment is very large compared to the wavelengths in S- or X-band so that the method of geometrical optics applies (ref. 6). Reflection from the segment should be substantially the same as for a complete sphere. For the case of direct backscatter the dimension across the segment need only be greater than $\sqrt{2\lambda r}$ (ref. 7). This is twice the size that would be required by a large flat disc to equal the cross section of the sphere. In estimating the actual extent of the spherical segment required for forward scatter, the assumption is made that the segment should be extended beyond the "bounce" point by an amount equal to the projection on the spherical arc of one-half the dimension required for direct backscatter.

The satellite is initially oriented toward the earth's center by an horizon-scan jet-reaction control system to an accuracy that can be better than a quarter of a degree. A solar sensor is used for third-axis control of yaw rate. If the orbit is nearly circular the reflecting surface is erected. Long-term orientation can be provided either by inertial-reaction controls working with the horizon scanner and powered by solar cells or for altitudes up to about 3 or 4,000 miles by the method of gravitational-gradient. In this case a secondary erectable structure separates the payload and the last-stage rocket booster a distance of about 60 feet at 3,000 miles altitude to provide static stability sufficient to overcome solar radiation pressure torques. If the orbit ellipticity is less than 0.02 the amplitude of oscillations due to this cause should be less than $\pm 2^{\circ}$ (refs. 9 and 10). Of course an orbit control system as described by Fitzgibbon (ref. 11) could be added and might be a required item to attain circular orbits at extreme altitudes.

The spherical diameter required to hold the path loss constant at varying altitude is presented in figure 4 for four cases. In case A we have assumed 85-foot and 60-foot dishes at 2,390 Mcs as for Project Echo. Starting at 900 miles with a diameter of 100 feet, the increase in diameter with altitude is rather tremendous. In case B with 150-foot dishes at 2,000 Mcs and a 100-foot diameter at 3,000 miles as suggested by Pierce, the increase in diameter is more reasonable. With the larger dishes the 100-foot diameter could be used to extremely high altitudes. This would decrease the number of satellites required. We will select case B to calculate the angle required for a spherical segment. This is shown in figure 5 for station distances of 0, 2,600, and 5,000 statute miles. Sketched in the upper right-hand corner are regions of mutual visibility at several altitudes, h_1, h_2, etc. When the satellite is at points S_X, the segment angle required is ϕ_X and similarly for points S_Y. Larger segments are required for S_Y points. Here is a possible trade-off. Since S_Y points correspond to greater path loss, it may be advantageous to make the segment somewhat less than ϕ_Y, particularly at lower altitudes. As the station distance increases, the segment angle decreases. If the satellite reflector were directly

overhead (direct back-scatter), the segment angle is quite small. It is not much greater if the segment is station-oriented.

Figure 6 illustrates a method of construction for an oriented reflector. The primary structure consists of an inflatable tube or a mast, an inflatable ring, and very fine steel wire spokes for alinement. The reflecting surface is a structure of inflatable honeycomb panels supported laterally by the lower set of rigging wires and a number of spacers. The reflector can be oriented either way toward the earth. It appears desirable to orient it upside down to prevent it from acting like a solar collector and thus to avoid high temperatures along the mast. In the design contemplated for the honeycomb the surface would be about 40 percent light-reflecting through use of an aluminum grid at 0.2-inch-square spacing. This would, however, permit reflection of radio waves as short as 5-cm wavelength. Based on this method of construction and the 150-foot dishes of case B, previously considered, some weight estimates have been made. These are presented in figure 7.

In figure 7 the weights do not include packaging, erection, or stabilization. We have plotted curves for spheres and for spherical segments. The weight of bare aluminum needed for 98-percent reflection, while small for a sphere at low altitudes, attains a value of 1 ton at 22,000 miles. For a segment at this altitude only 12 pounds of aluminum is needed. Unfortunately there appears no possible way to make an all-aluminum configuration with a thickness of 2,200 angstroms and, if we could, it would be greatly disturbed by solar radiation pressure. If the Project Echo 100-foot sphere were made larger while retaining the same thickness of material, the weight for larger spheres becomes prohibitive above about 8,000 miles for an Atlas type launching vehicle. If the material thickness is increased in proportion to spherical diameter, the weight becomes too great at about 5,800 miles. Further, if the spheres are rigidized, the weight barrier occurs at about 4,200 miles. For rigid spherical segment reflectors that are earth-oriented, the weight barrier occurs between 10,000 and 15,000 miles altitude. If, however, the spherical segment reflectors are oriented equally toward a pair of ground stations, the weight barrier is removed. For a reflector that is station-oriented at 22,000 miles altitude, the reflector weight is estimated to be of the order of 50 pounds with 150-foot ground antennas.

Let us look next at a summary of the payload weight for an earth-oriented segment reflector for use at 3,000 miles altitude and working with 150-foot dishes, as shown in table 4. This reflector has a spherical diameter of 100 feet, a rim diameter of 56.6 feet, and a 70° spherical angle. The weight for the segment is 60 pounds and the total weight for both initial and long-term stabilization is 51 pounds when both control systems are of an active type or 35 pounds if a passive gravity system

is used for long-term stability. The total weight is about 70 percent of the Project Echo payload weight or 25 percent of the payload weight for a rigidized 100-foot sphere. Furthermore, if a segment with 100-foot spherical diameter were matched with larger dishes, the payload weight would decrease with altitude, as shown by figure 8. Here you see the dishes increase in size to about 700-foot diameter at 22,000 miles satellite altitude. The payload decreases to about 43 pounds and the reflector rim diameter to 15 feet. At this altitude most of the weight is in the stabilization systems. If a 100-foot sphere were used with these larger dishes, its payload weight would of course remain constant.

COMPARISON OF SYSTEMS

Let us try to sum all this up by comparing four passive relay systems, keeping in mind, among other considerations the relative cost. The essential features of each system are shown in table 5. There are two low-altitude systems and two 24-hour "stationary" systems. Dish sizes are either 150 feet or 700 feet. For the 24-hour systems the dishes are nonsteerable and only two are required to communicate between two stations. This appreciably reduces the cost of the dishes. Likewise, since there is only one satellite, the ground computing and tracking are simpler. For the low-altitude systems we assume that 24 reflectors are needed and that Centaur launching vehicles are loaded up to capacity with a number of these reflectors which become randomly distributed in orbit. For the 100-foot rigid spheres, approximately four vehicles are needed, while for the 100-foot spherical segment reflectors only one is required. Since both low-altitude systems perform the same job, the cost for the earth-oriented relay system appears to be of the order of one-half that of the sphere system. For the high-altitude systems, one Thor-Agena vehicle may be adequate in each case and both systems should have 100-percent probability of continuous communication compared to about 99 percent for the low-altitude systems. The relative cost for the earth-oriented segment and 700-foot dish is of the order of one-half, although the transmitting power cost is necessarily greater. The station-oriented segment appears to be the cheapest system for two-station transmission. However, it can not serve as many stations.

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TABLE I

DISTANCE BETWEEN SOME PRINCIPAL CITIES

NEW YORK AND LOS ANGELES	2,400 STATUTE MILES
NEW YORK AND LONDON	3,500 *
NEW YORK AND MOSCOW	4,600
NEW YORK AND RIO DE JANEIRO	4,800
LOS ANGELES AND ANCHORAGE	2,300
LOS ANGELES AND HONOLULU	2,600
LOS ANGELES AND TOKYO	5,700
HONOLULU AND SIDNEY	5,000
HONOLULU AND TOKYO	3,800

* DISTANCE BETWEEN NEWFOUNDLAND AND ISLE OF LEWIS IN THE HEBRIDES, SCOTLAND (CONSIDERED BY PIERCE) IS 2,060 MILES.

TABLE II

AVAILABILITY OF LARGE GROUND-BASED PARABOLIC ANTENNAS

Diameter of dish, ft	Dish mechanically steerable	Maximum frequency MCS	Approximate number	Location	Status
60	Yes	≈4000	9	Holmdel, N. J.; Stump Neck, Md.; Wallops Island; Sugar Grove, West Va.; Fla.; Calif.	Majority in operation
72	Yes		1	Several hours dr. from Moscow	In operation
84	Yes		2	Millstone Hill, Mass.	In operation
		2270 (Tri)		Trinidad	In operation
		10000 (W. Va.)		Green Bank, W. Va.	
85	Yes		7	Goldstone, Calif.	In operation
				Lassen Nt'l. For., Calif.	Under constr.
				Ann Arbor, Mich.	In operation
				Woomera, Australia	Under constr.
				South Africa	Planned
				South Pt., Hawaii	In operation
140	Yes	10000	1	Green Bank, W. Va.	Under constr.
142	Yes	2000	1	Stanford, Calif.	Constr. in 1960
250	Yes		1	Joddrell Bank, England	In operation
600	Yes*	4000	1	Sugar Grove, W. Va.	Under constr.
1000	No**	440	1	Puerto Rico	Under constr.

*Also has adjustable panels for improved focusing.

**But beam sweep ±20° from vertical.

TABLE III

PAYLOAD WEIGHT, LB, FOR 100 FT SPHERE

ITEM	PROJECT ECHO 1/2 MIL MYLAR 2200 ANGSTROMS AL		RIGIDIZED* (EST.)	
SPHERE				
ALUMINUM	4.0		276	
MYLAR	132.0		132	
SUBTOTAL		136.0		408
INFLATION SYSTEM				
INITIAL ≠	6.8		30	
LONG TERM #	20.0		—	
SUBTOTAL		26.8		30
BEACONS (2)		2.4		2.4
CONTAINER**		21.7		66
TOTAL		186.9		506

* INFLATABLE HONEYCOMB
≠ WATER SYSTEM
SUBLIMING SYSTEM
** FOR PROJECT ECHO, 26.6 INCH SPHERE
FOR RIGIDIZED, 38 INCH SPHERE

TABLE IV
PAYLOAD WEIGHT FOR SPHERICAL SEGMENT

$D = 100$ FT, $d = 56.6$ FT, $2\phi = 70°$

3,000 MILE DESIGN ALTITUDE, EARTH-ORIENTED

ITEM	WEIGHT, LB			
SPHERICAL SEGMENT				
INFLATABLE PANELS	36			
RIM AND BRACING	24			
SUBTOTAL			60	
INFLATION SYSTEM				
INFLATABLE PANELS	3			
RIM AND BRACING	2			
SUBTOTAL			5	
BEACON (1)			1.2	
CONTAINER **			15	(17)
STABILIZATION				
INITIAL *	25			
LONG TERM ≠	26	(10)		
SUBTOTAL			51	(35)
TOTAL			132	(118)

* HORIZON SCANNER, JET CONTROLS, BATTERIES, ETC.

≠ ADD FLYWHEEL CONTROLS, SOLAR CELLS, BATTERIES, OR (ADD GRAVITY STABILIZATION)

** 22-INCH SPHERE

TABLE V
RELATIVE COST OF SYSTEMS

FOR COMMUNICATION BETWEEN A AND B AT LAT. ≈53°, AB = 2,060 MILES

ALTITUDE	DISHES AT A AND B		SATELLITES		BOOSTERS		RELATIVE COST
MILES	SIZE	NO.	TYPE	NO.	TYPE	NO.	
3,000	150	4	100' RIGID SPHERE (506#)	24	CENTAUR	4	1
3,000	150	4	100' SEGMENT ≠ (132#)	24	CENTAUR	1	1/2
22,300*	700**	2	100' SEGMENT ≠ (≈100#)	1	THOR-AGENA	1	1/2
22,300*	150**	2	2254' SEGMENT # (≈150#)	1	THOR-AGENA	1	1/4

* REQUIRES EQUATORIAL LAUNCH SITE

** NON-STEERABLE DISHES BUT BEAM SCANS ±20° FROM AXIS, 2,000 Mcs

≠ EARTH-ORIENTED

STATION-ORIENTED

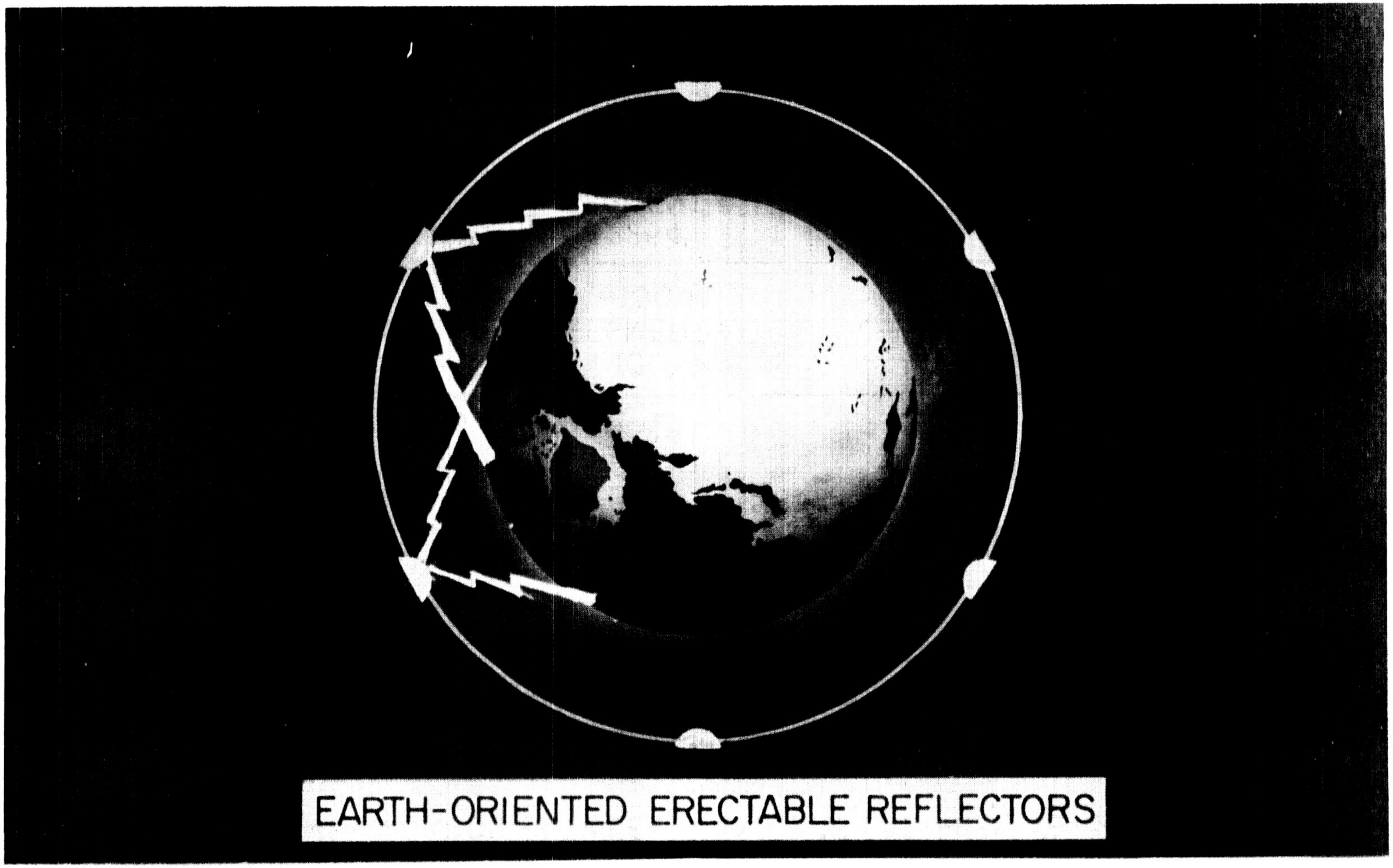

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Figure 1.- Radio communication by forward scattering satellites.

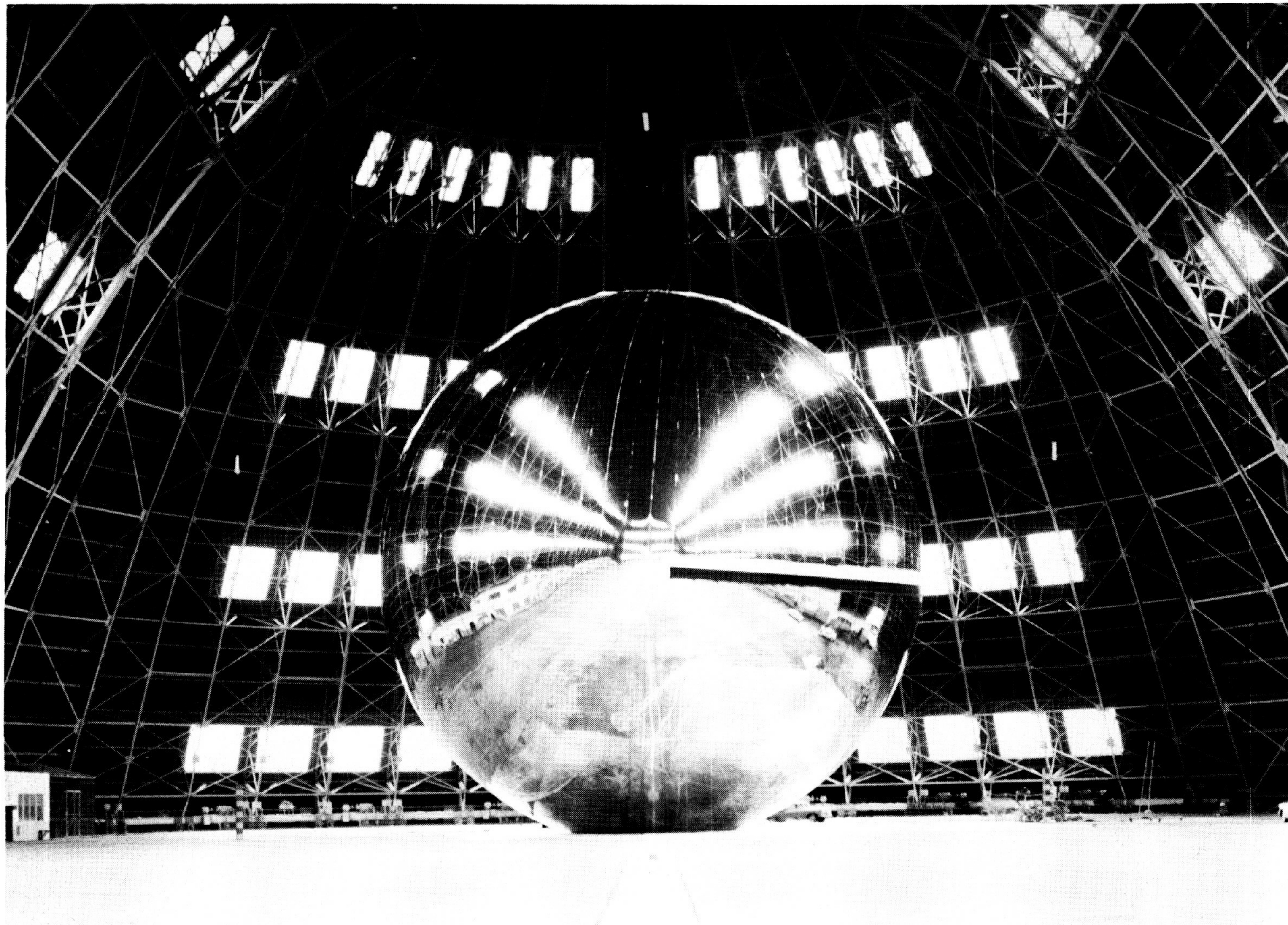

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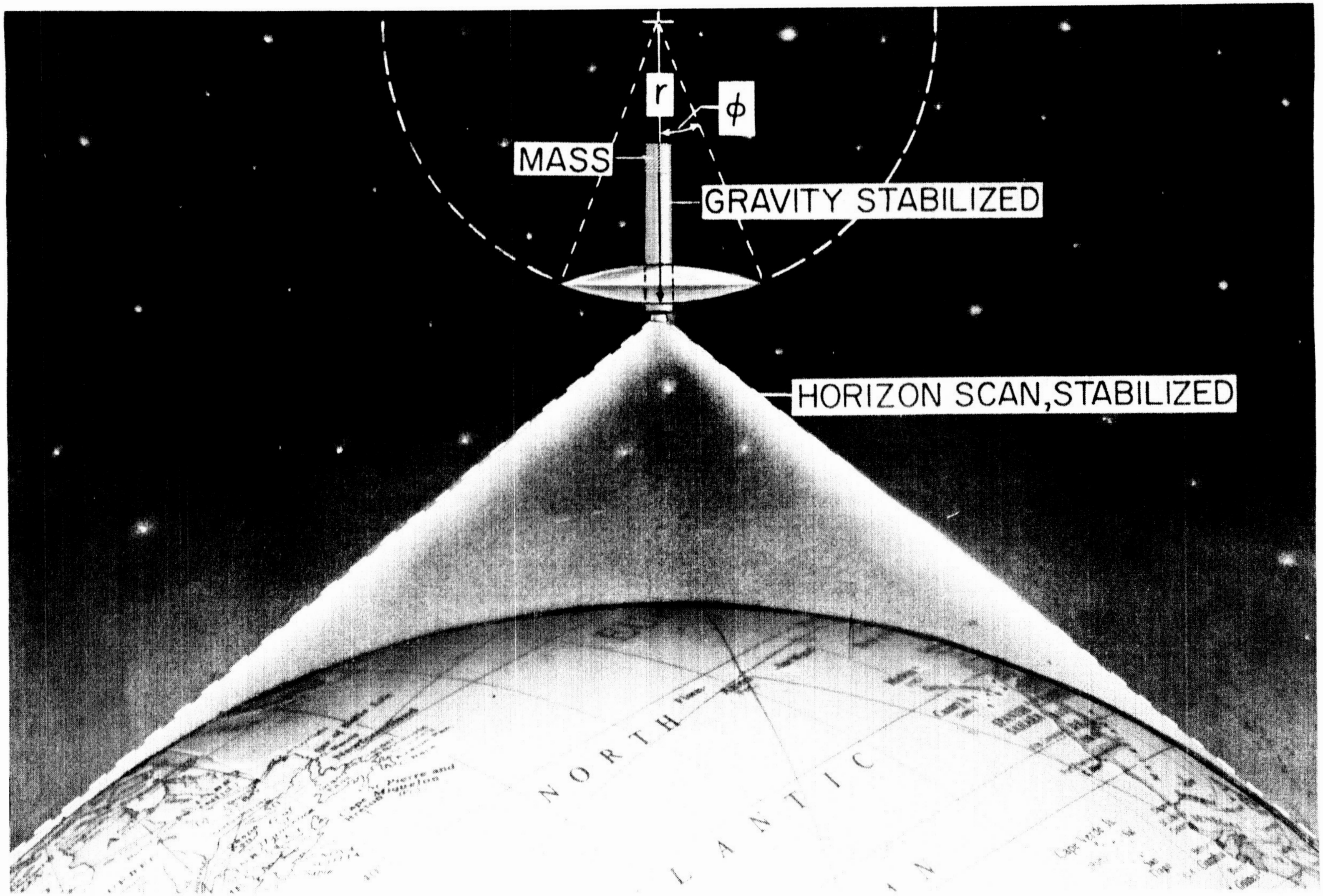
Figure 2.- Project Echo 100-foot inflatable satellite.



NASA

Figure 3.- Communications relay, passive-type, stabilized.

CASE	L, MAX. PATH LOSS	DISH SIZES	Mcs	BEAM ELEV.
A	181.2 DB	85',60'	2390	6°
B	183.4	150,150	2000	6°
C	183.4	300,300	2000	6°
D	183.4	600,600	2000	6°

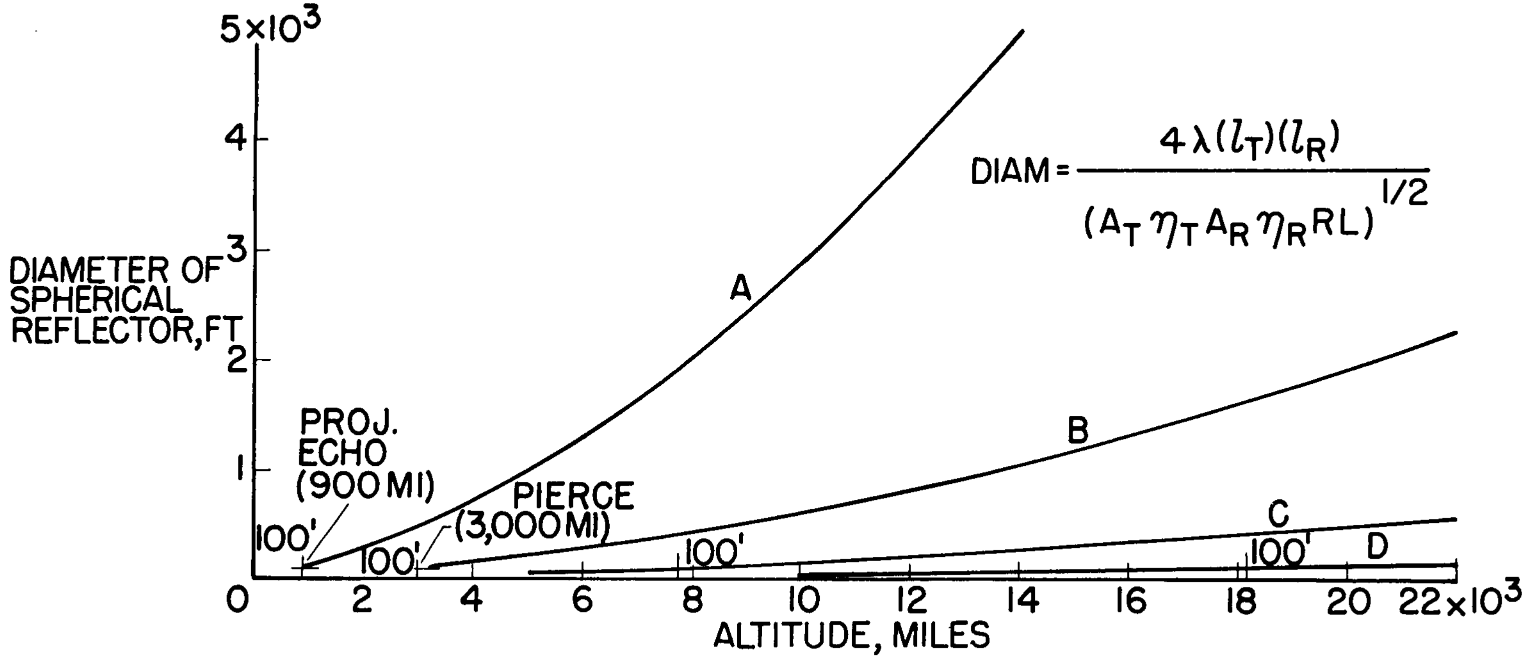


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Figure 4.- Size of spherical reflector for constant path loss at altitude.

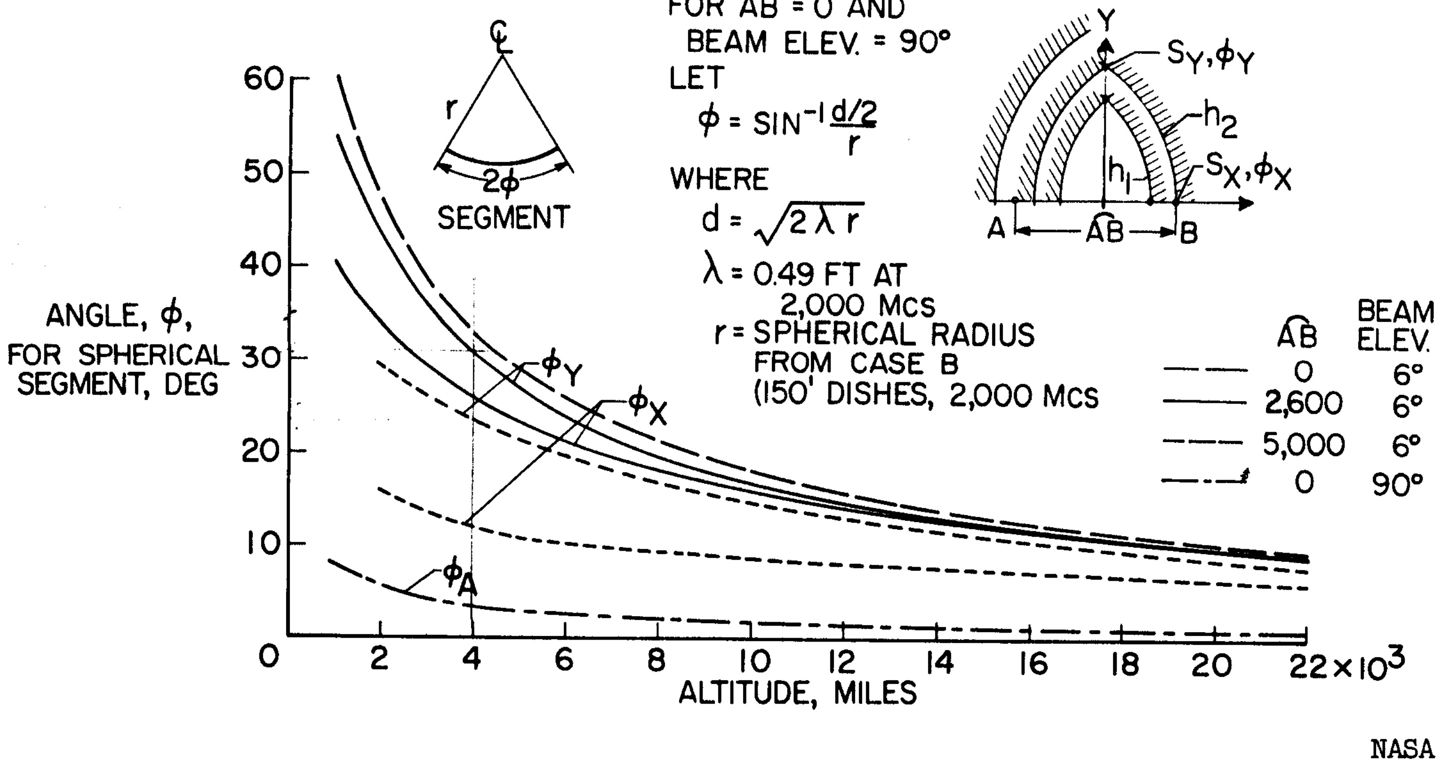

Figure 5.- Angle required for spherical segment, earth-oriented.

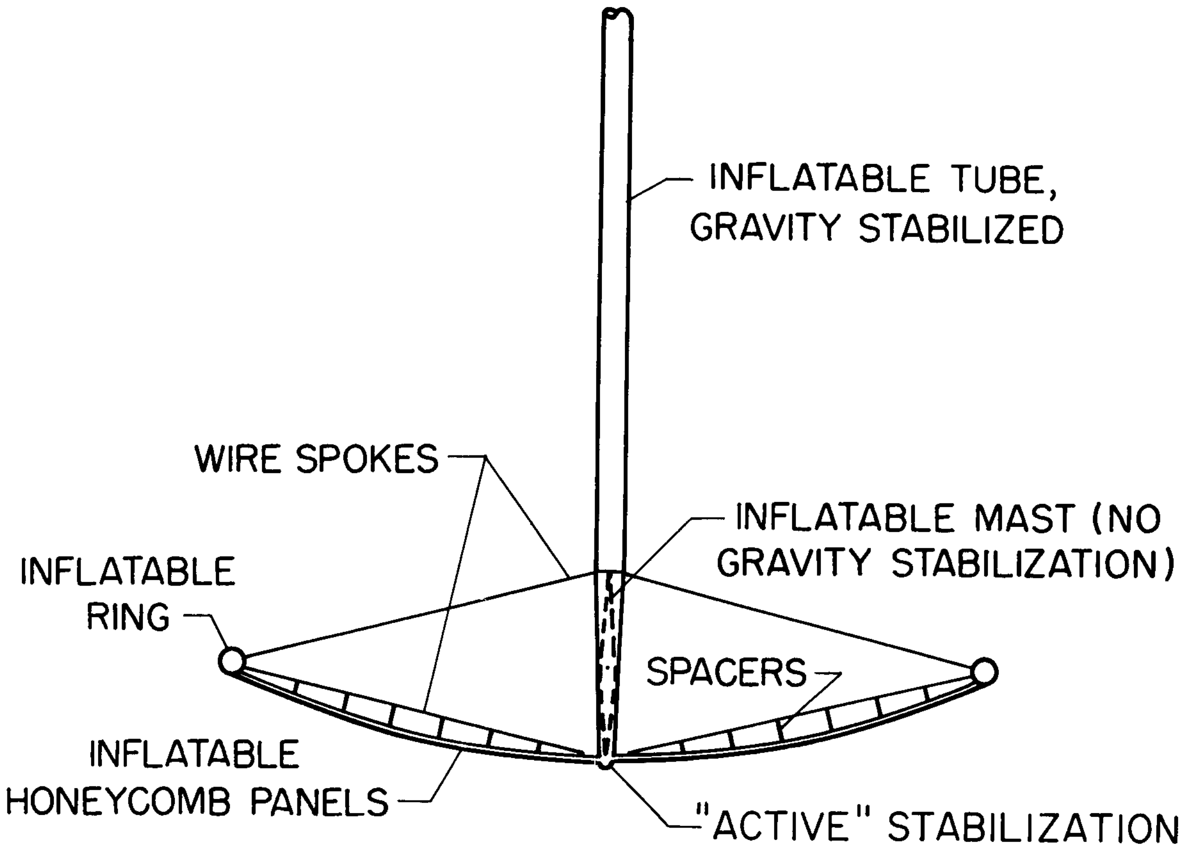

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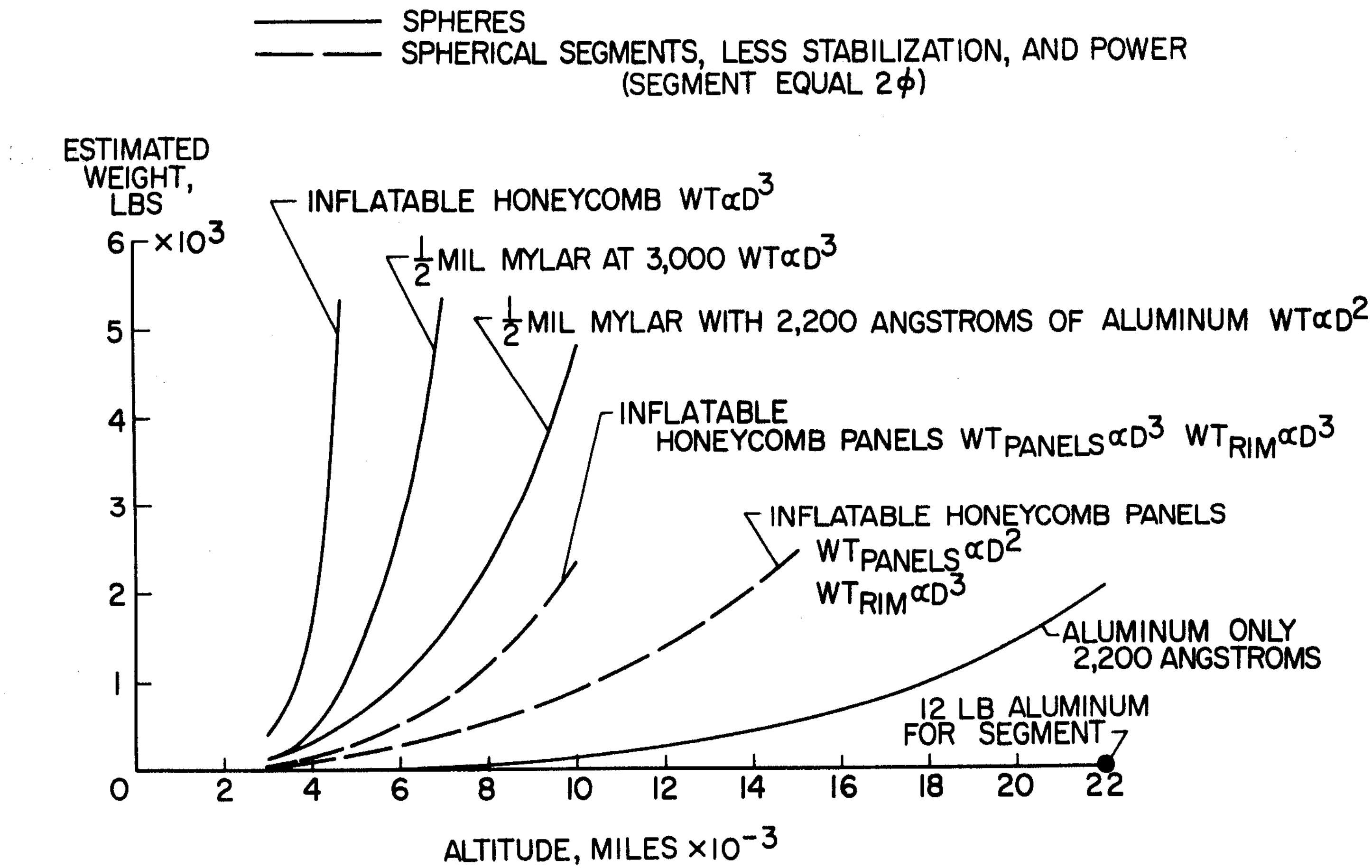
Figure 6.- A method of construction for oriented reflector.



NASA

Figure 7.- Weight comparison of passive reflectors based on 150-foot dishes and 2000 Mcs, less weight for packaging and erection. Beam elevation is 6°.

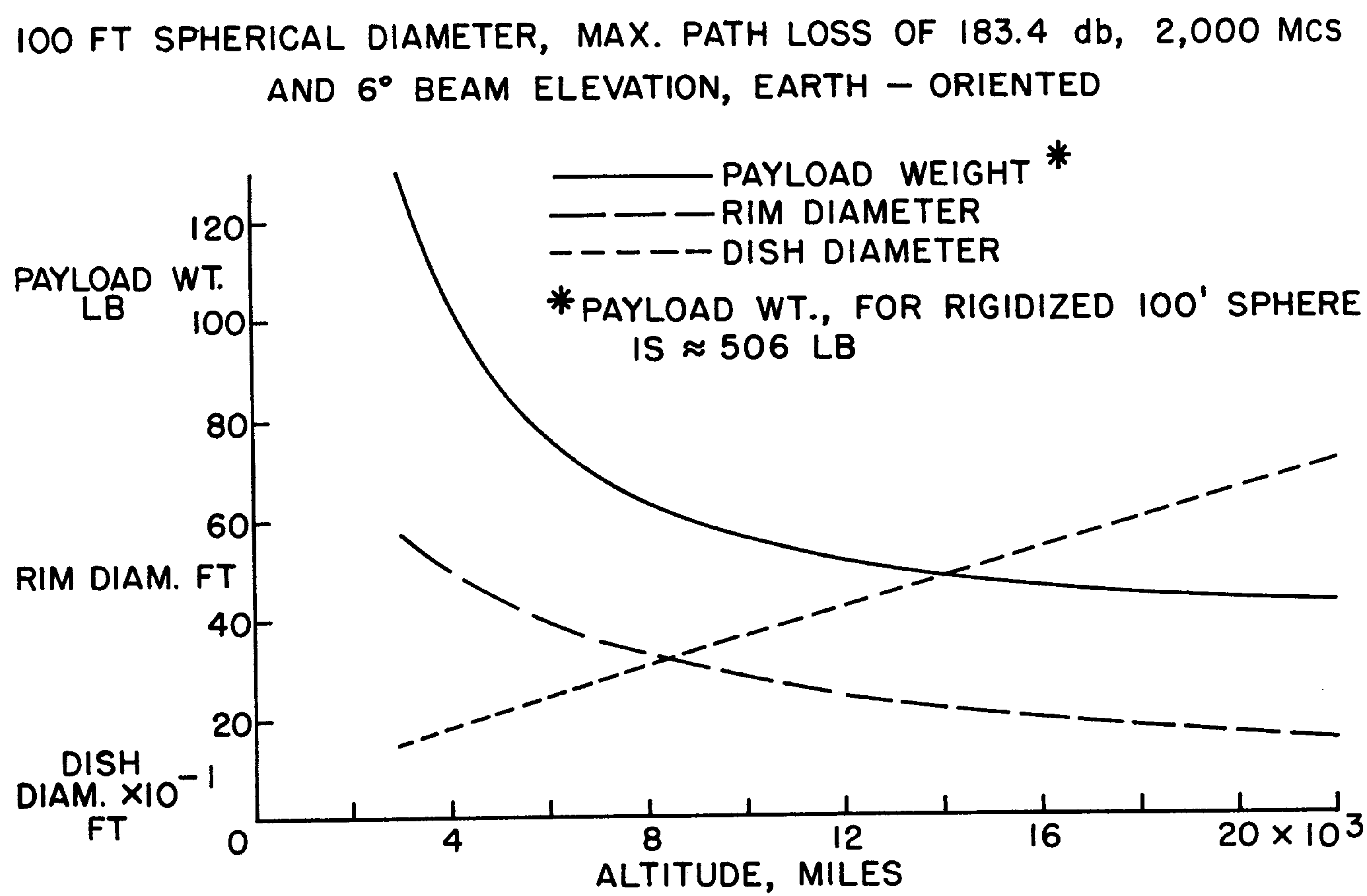


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Figure 8.- Dish size, satellite rim size, and payload weight for spherical segment reflector, earth-oriented.